Army Research Laboratory

Calibration and Verification Procedures at ARL for the Focus Microwaves Load Pull System

by Benjamin D. Huebschman

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Benjamin D. Huebschman
Sensors and Electron Devices Directorate, ARL

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14. ABSTRACT

When evaluating the performance of technologically innovative microwave devices, it is important to be able to validate the performance of the system performing the measurements. The theory behind the measurements used in recent Army Research Laboratory testing of the Gallium Nitride high electron mobility transistor devices is described. The verification of calibration used in the measurement is outlined in detail including a metric by which the accuracy of the validation can be judged.

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Calibration, microwave, TRL, verification, load pull

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1. Introduction

The Army Research Laboratory (ARL) is participating in the Defense Advanced Research Projects Agency (DARPA) Wide Bandgap Semiconductor Initiative (WBSCI) as part of the tri-service evaluation team. The ARL role during phase two of this program is to measure and report on the performance of the high frequency power amplifier transistor being developed by Northrop Grumman. The frequency at which the power amplifier is being evaluated is 40 GHz. The high frequency at which the devices are being evaluated creates a number of problems.

A microwave engineer working on components at these frequencies with standard Vector Network Analyzers (VNA) and radio frequency (RF) power equipment must have an understanding of the calibration and verification process in order to be aware of the factors that would lead to erroneous measurements. At the higher frequencies the system becomes increasingly sensitive to mechanical deformation. Often measurements that appear valid could in fact be inaccurate. Frequently discrepancies will arise in the data being measured at separate locations. When representing this data to a supported customer, an engineer must be able to speak intelligently about the calibration, verification, and measurement process to establish confidence in the measurement results. In this document, the calibration and verification procedure developed at ARL in support of the WBSCI will be discussed. It begins with the underlying theory behind the calculations and then describes the actual calibration techniques. The verification techniques are also described. Included in this discussion are the criteria upon which a calibration would be accepted or rejected.

2. Theory

There are a number of methods used to characterize a microwave system. Some of the most ubiquitous parameters that describe a two port microwave system are the so called S-parameters. A discussion of S-parameters is beyond the scope of this document. If the reader requires a greater understanding of S-parameters, refer to the text by Pozar (*1*).

In order to determine the performance of a device, it is necessary to have a method to use measurements on the ports of the VNA to describe the RF state at the device-under-test (DUT). Typically, components are modeled as matrix blocks and de-embedded to the desired reference plane. There is an input block and an output block. It is a non-trivial exercise to determine the S-parameters of these blocks, though a number of techniques exist to do so. The one described in this document is the Thru Reflect Line (TRL) technique. The VNA has built in software that allows the use of a calibration kit to de-embed the measurements to the tips of the cable. The Focus software has an algorithm to de-embed the measurements to the probe tips using an on wafer calibration standard. Both Focus and Agilent allow for TRL calibration.

2.1 Thru Reflect Line (TRL)

The TRL is a well known calibration technique. It is included here for completeness, and because often when encountered in literature or publications it is incorrectly explained or contains an error. The TRL calibration requires four measurements and produces two S-parameter blocks, one for each of the blocks on the two ports of the measurement system. Figure 1 is a graphic representation of the system.

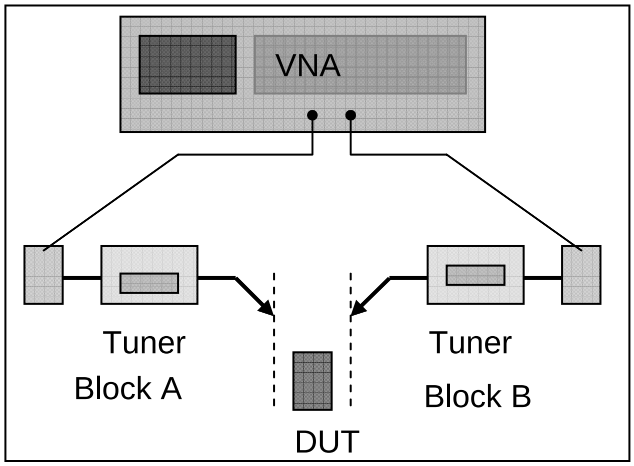

Figure 1. Block diagram of TRL calibration system.

The four measurements are taken from well know standards. Measurements are

1. thru line
2. delay line
3. short circuit measurement on port 1
4. short circuit measurement on port 2

To mathematically manipulate the blocks they must be converted from S-parameters, which contain information in an easily readable format, to matrices which can be cascaded using standard matrix algebra. There are several common used matrices like this used in microwave engineering. The one best suited for our purposes is the T-matrix.

The equations

$$T_{11} = \frac{1}{S_{21}} \tag{1a}$$

$$T_{12} = -\frac{S_{22}}{S_{21}} \tag{1b}$$

$$T_{21} = \frac{S_{11}}{S_{21}} \tag{1c}$$

$$T_{22} = S_{12} - \frac{S_{11}\,S_{22}}{S_{21}} \tag{1d}$$

During our derivation we will be making use of T-matrices and S-matrices.

We assume our calibration standards have the following S-parameters

$$S_{THRU} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$S_{LINE} = \begin{pmatrix} 0 & e^{i\theta} \\ e^{i\theta} & 0 \end{pmatrix}$$

The short circuits have a reflection coefficient of –1. Using equations 1a through 1d we can calculated the T-matrices for the thru and the delay line.

$$T_{THRU} = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

$$T_{LINE} = \begin{pmatrix} e^{-i\theta} & 0 \\ 0 & e^{i\theta} \end{pmatrix}$$

We are trying to determine the modeling parameters for the input and output blocks. We have the theoretical values for the calibration standards and measured values for these standards cascaded with the input and output blocks. Our notation for these will be A and B for the input and output blocks, respectively, and ML for the measured delay line and MT for the measured thru.

Therefore,

$$T_{MT} = T_A T_{THRU} T_B = T_A T_B \tag{2}$$

since the thru T-matrix is the identity matrix.

Likewise the delay line equation can be represented by

$$T_{ML} = T_A T_{LINE} T_B \tag{3}$$

Solving for the output block transfer matrix using equation 2 we get

$$T_B = T_A^{-1} T_{MT} \tag{4}$$

If we substitute for Tb in equation 3, we derive the following equation

$$T_{ML} = T_A T_{LINE} T_A^{-1} T_{MT}$$

which can be written as

$$T_{ML} T_{MT}^{-1} = T_A T_{LINE} T_A^{-1}$$

and

$$T_{ML} T_{MT}^{-1} T_A = T_A T_{LINE} \tag{5}$$

We will use the following notation for the product of the measured line matrix and the inverse of the measured thru.

$$T_{ML} T_{MT}^{-1} = T_{LT}$$

This substitution in equation 5 gives

$$T_{LT} T_A = T_A T_{LINE}$$

which can be written as

$$\begin{pmatrix} T_{LT11} & T_{LT12} \\ T_{LT21} & T_{LT22} \end{pmatrix} \begin{pmatrix} T_{A11} & T_{A12} \\ T_{A21} & T_{A22} \end{pmatrix} = \begin{pmatrix} T_{A11} & T_{A12} \\ T_{A21} & T_{A22} \end{pmatrix} \begin{pmatrix} e^{-i\theta} & 0 \\ 0 & e^{i\theta} \end{pmatrix} \tag{6}$$

written in equation form

$$T_{LT11} T_{A11} + T_{LT12} T_{A12} = T_{A11} e^{-i\theta} \tag{7a}$$

$$T_{LT21} T_{A11} + T_{LT22} T_{A21} = T_{A21} e^{-i\theta} \tag{7b}$$

$$T_{LT11} T_{A12} + T_{LT12} T_{A22} = T_{A12} e^{i\theta} \tag{7c}$$

$$T_{LT21} T_{A12} + T_{LT22} T_{A22} = T_{A22} e^{i\theta} \tag{7d}$$

Equation 7a divided by 7b can be written as

$$T_{LT21} \left(\frac{T_{A11}}{T_{A21}} \right)^2 + \left(T_{LT22} - T_{LT11} \right) \frac{T_{A11}}{T_{A21}} - T_{LT12} = 0 \tag{8a}$$

Equation 7c divided by 7d can be written as

$$T_{LT21} \left(\frac{T_{A12}}{T_{A22}} \right)^2 + \left(T_{LT22} - T_{LT11} \right) \frac{T_{A12}}{T_{A22}} - T_{LT12} = 0 \tag{8b}$$

Upon inspection we see that the coefficients are the same. However, we know that the two variable terms are uniquely defined. Quadratic equations have two solutions. From these facts we can determine that one of the solutions to the quadratic equation is

$$\left(\frac{T_{A12}}{T_{A22}}\right) \text{ and the other is} \left(\frac{T_{A11}}{T_{A21}}\right).$$

From equation 1 we can determine that

$$S_{A11} = \frac{T_{A12}}{T_{A22}} \tag{9}$$

Likewise substitution allows us to determine that

$$\frac{T_{A11}}{T_{A21}} = S_{A11} - \frac{S_{A12}S_{A21}}{S_{A22}} \tag{10}$$

We expect that our blocks will be designed primarily to facilitate transmission of power to the DUT. From this it follows that Sa11 will be much smaller than Sa12 and Sa21. Using this principle we can consistently assign the smaller magnitude quadratic root of equation 8a and 8b to be the Sa11 term while the larger magnitude quadratic root is shown in equation 10.

Therefore, the difference of the roots can be written as

$$\frac{T_{A12}}{T_{A22}} - \frac{T_{A11}}{T_{A21}} = S_{A11} - \left(S_{A11} - \frac{S_{A12}S_{A21}}{S_{A22}}\right) = \frac{S_{A12}S_{A21}}{S_{A22}} \tag{11}$$

A similar derivation can be used to isolate the parameters of the output block.

To begin, we start with equations 2 and 3, and isolate Tb instead of Ta

$$T_{MT} = T_A T_{THRU} T_B = T_A T_B$$

$$T_A = T_{MT} T_B^{-1}$$

Substituting into equation 3

$$T_{ML} = T_A T_{LINE} T_B$$

$$T_{ML} = T_{MT} T_B^{-1} T_{LINE} T_B \tag{12}$$

$$T_{MT}^{-1} T_{ML} = T_B^{-1} T_{LINE} T_B$$

Writing the left hand side as

$$T_{MT}^{-1} T_{ML} = T_{TL}$$

$$T_{TL} = T_B^{-1} T_{LINE} T_B$$

$$T_B T_{TL} = T_{LINE} T_B$$

in matrix form

$$\begin{pmatrix} T_{B11} & T_{B12} \\ T_{B21} & T_{B22} \end{pmatrix}\begin{pmatrix} T_{TL11} & T_{TL12} \\ T_{TL21} & T_{TL22} \end{pmatrix} = \begin{pmatrix} e^{-i\theta} & 0 \\ 0 & e^{i\theta} \end{pmatrix}\begin{pmatrix} T_{B11} & T_{B12} \\ T_{B21} & T_{B22} \end{pmatrix} \tag{13}$$

expanding into equations

$$T_{TL11}T_{B11} + T_{TL21}T_{B12} = T_{B11}e^{-i\theta}$$

$$T_{TL12}T_{B11} + T_{TL22}T_{B12} = T_{B12}e^{-i\theta}$$

$$T_{TL11}T_{B21} + T_{TL21}T_{B22} = T_{B21}e^{i\theta}$$

$$T_{TL12}T_{B21} + T_{TL22}T_{B22} = T_{B22}e^{i\theta}$$

Putting this into quadratic form yields the equations below.

$$T_{TL12}\left(\frac{T_{B11}}{T_{B12}}\right)^2 + \left(T_{TL22} - T_{TL11}\right)\frac{T_{B11}}{T_{B12}} - T_{TL21} = 0$$

$$T_{TL12}\left(\frac{T_{B21}}{T_{B22}}\right)^2 + \left(T_{TL22} - T_{TL11}\right)\frac{T_{B21}}{T_{B22}} - T_{TL21} = 0$$

Solving we get

$$S_{B22} = -\frac{T_{B21}}{T_{B22}}$$

which is the root that should have the smaller magnitude.

The root with the larger magnitude is

$$\frac{T_{B11}}{T_{B12}} = -S_{B22} + \frac{S_{B21}\,S_{B12}}{S_{B11}}$$

the difference between the two is

$$\frac{T_{B11}}{T_{B12}} - \frac{T_{B21}}{T_{B22}} = -S_{B22} + \frac{S_{B21}\,S_{B12}}{S_{B11}} + S_{B22} = \frac{S_{B21}\,S_{B12}}{S_{B11}} \tag{14}$$

Now we will use this information along with the measured values for the reflections to determine the rest of the S parameters.

A well known one port reflection equation is shown below

$$\Gamma_{MA} = S_{A11} + \frac{S_{A21}\,S_{A12}\Gamma_R}{1 - S_{A22}} \tag{15}$$

The left side of the equation is the measured value of port one when the probes are on the reflection standard. Γ_R is the nominal reflection coefficient. In this technique, the reflection coefficient (Γ_R) is not assumed to be known, but rather it is isolated and eliminated. As a check, when the S-parameters are known, the predicted value for the reflection coefficient can be inserted into the equation to verify that both sides of equation 15 are equal.

If we solve for the reflection coefficient and substitute for the know values already determined we get

$$\Gamma_R = \frac{1}{S_{A22}} \frac{\frac{T_{A12}}{T_{A22}} - \Gamma_{MA}}{\frac{T_{A11}}{T_{A21}} - \Gamma_{MA}} \tag{16}$$

We will do the same for our port two equations.

$$\Gamma_{MB} = S_{A22} + \frac{S_{B21}\,S_{B12}\Gamma_R}{1 - S_{B11}} \tag{17}$$

can be turned into

$$\Gamma_R = \frac{1}{S_{B11}} \frac{S_{B22} + \Gamma_{MA}}{\frac{T_{B11}}{T_{B12}} + \Gamma_{MA}} \tag{18}$$

Setting equations 15 and 17 equal to each other we get

$$S_{A22} = S_{B11} \frac{S_{A11} - \Gamma_{MA}}{\frac{T_{A11}}{T_{A21}} - \Gamma_{MA}} \frac{\frac{T_{B11}}{T_{B12}} + \Gamma_{MA}}{S_{B22} + \Gamma_{MA}} \tag{19}$$

All of these values are known except for Sa22 and Sb11. We can use our measurement for the reflection on the thru measurement to get another equation relating Sa22 and Sb11.

$$S_{A22} = \frac{1}{S_{B11}} \frac{S_{A11} - \Gamma_{MAT}}{\frac{T_{A11}}{T_{A21}} - \Gamma_{MAT}} \tag{20}$$

Where

$$\Gamma_{MAT} = S_{THRU11}$$

S_{THRU11} is the port 1 refection S parameter of the Thru measurement; or to put it differently, it is the S_{11} of the Thru measurement.

Plugging equations 18 into 19, we get.

$$S_{A22} = \frac{S_{A11} - \Gamma_{MA}}{\frac{T_{A11}}{T_{A21}} - \Gamma_{MA}} \frac{\frac{T_{B11}}{T_{B12}} + \Gamma_{MA}}{S_{B22} + \Gamma_{MA}} \frac{S_{A11} - \Gamma_{MAT}}{\frac{T_{A11}}{T_{A21}} - \Gamma_{MAT}} \tag{21}$$

The sign of Sa22 can be determined by inserting determined values into equation 15 and ensure that the equation balances when the reflection coefficient is the predicted value.

With Sa22 known, we can determine Sb11 from equation 19.

Using Sa22 and Sb11 with our previously know data, the remaining, unknown S-parameters can be extracted from equations 11 and 14 when written as shown below. It is impossible to mathematically isolate the transfer terms (S12 and S21).

$$S_{A12}S_{A21} = \left(S_{A11} - \frac{T_{A11}}{T_{A21}} \right) S_{A22} \tag{22}$$

$$S_{B12}S_{B21} = \left(\frac{T_{B11}}{T_{B12}} - S_{B22} \right) S_{B11} \tag{23}$$

With the four S-parameters of the input and output blocks, we can calculate T-matrices that can be de-embedded from our measurements to determine performance of the DUT.

Understanding the calculations that go into the derivations of the input and output blocks in the TRL calculation allows the engineer to determine when these calculations become inaccurate.

2.2 GT Calc

The method of verifying our calibration involves measuring the gain of our system with the probes landed on a thru line while the tuners are swept through a load pull and a source pull. The measured gain at every point is compared to the calculated gain. In this section the technique for calculating gain is described.

The transducer gain of an arbitrary DUT can be written as:

$$G_T = \frac{1-|\Gamma_S|^2}{|1-\Gamma_{IN}\Gamma_S|^2}|S_{21}|^2\frac{1-|\Gamma_L|^2}{|1-S_{22}\Gamma_L|^2} \tag{24}$$

Of key interest is the notation used in this equation. The notations S and L refer respectively to the source and load plane as seen by the DUT. S-parameters are the S-parameters of the DUT. The term Γ_{IN} is the input reflection coefficient of the DUT. The equation of which is shown below:

$$\Gamma_{IN} = S_{11} + \frac{S_{21}S_{12}\Gamma_L}{1-S_{22}\Gamma_L} \tag{25}$$

For the verification, the DUT is a thru. The S-parameters for a thru, as previously mentioned, are shown below.

$$S_{THRU} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \tag{26}$$

Filling these values into equation 25, this equation simplifies to

$$\Gamma_{IN} = \Gamma_L \tag{27}$$

and equation 24 simplifies to

$$G_T = \frac{(1-|\Gamma_S|^2)(1-|\Gamma_L|^2)}{|1-\Gamma_L\Gamma_S|^2} \tag{28}$$

which is the equation we use for our calculated Gt. This is the equation we will use when discussing our load pull verification.

---

3. Calibration

The high frequency load pull system used by ARL in support of the WBSCI uses the Focus Microwaves Winpower software as well as Focus Microwaves tuners.

3.1 Passive Blocks

The Focus Software operates in an intuitive straight forward manner. The S-parameters of different blocks are measured on the VNA. These are then converted into transfer matrices and cascaded. In figure 2, the power is measured at the input through a coupler and at the output.

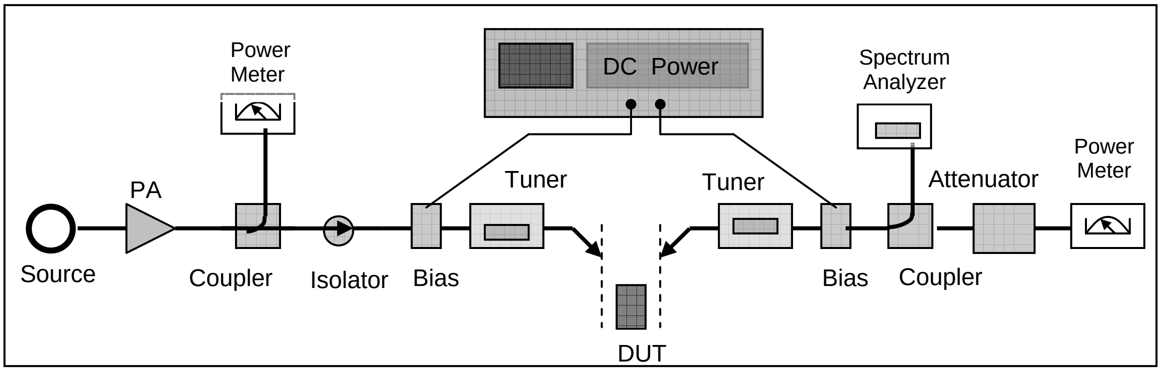

Figure 2. Block diagram for the power measurement system.

The following S-parameter measurements are taken:

1) The input block. This is a measurement of the filter, coupler, and isolator.

2) The input coupler. In this measurement, port 1 is in the same location as that of the input block. Port 2 is connected to the coupled port of the coupler. By comparing this measurement with the previous one, the Focus software can use a measurement on the input power meter to determine the power incident on the bias T and tuner.

3) The output block. This measurement consists of the output coupler and attenuators. It is the sum of all elements between the output bias T and the power meter. By using this block, the software can determine the power leaving the tuner and bias T, given the power at the output power meter.

When making measurements, it is important to try to get the configuration of the passive elements as close as possible to that of the system in operation. At high frequency, the S-parameters are very sensitive to slight geometric deformation. Flexible cable should be in the configuration that will be used during power measurements. Semi-rigid cables and waveguides should avoid being stressed in a manner different from system operation. The power meter should remain connected during the input block S-parameter measurement, and the port 2 of the input block should be connected to the bias T during the input coupler measurement.

With these measurements, we can determine the power incident upon and leaving from the bias Ts at each side of the tuners.

3.2 Tuner Calibration

Tuner calibration is also controlled by the Focus software. Figure 1, shown previously in the report, shows the layout of the setup for the calibration of the tuners. This is identical to the setup for the TRL calibration. For a tuner calibration, the DUT is a thru.

The tuners sweep through a range of reflection coefficients by inserting a metal probe into an air line and moving the probe different distances from the DUT. At each position of the tuner, the

S-parameters of that block are measure. This is accomplished through a simple de-embedding calculation. The tuner not being measured is moved to its initialization configuration. This configuration corresponds to the S-parameter block measured in the TRL calibration. With the opposite block in a well known state, the S-parameters of each tuner configuration can be calculated by measuring the total S-parameters in each configuration and de-embedding the known values.

3.3 Verification

No calibration is complete until it has been verified. There are several important criteria for a verification test. The system must be as close as possible to the final state of operation. Ideally, it should be in the state that will be used during the measurement. A second criterion for a verification test is that the test should compare a predicted value with a measured value. If the system is to be operated in a range of conditions, then the verification should be made over a range of conditions with the statistics of these measurements analyzed. Also, the criteria for the success or failure of the verification should be known and stated ahead of time. Without stated success criteria, it is easy for an engineer to decide that the verification is close enough or good enough. Precisely articulated criteria for a valid verification ensure that measurement system's tolerances for accuracy do not degrade over time, and that as anomalies begin to arise they are routinely isolated and dealt with.

3.4 Load/Source Pull

The Load/Source Pull measurement is designed to accomplish two tasks: determine the error correction factors and verify the tuner calibration by establishing a figure of merit for the load/source pull sweep. The procedure for the Load/Source Pull verification is very similar to that of the tuner calibration. The power measurement system is assembled into its operational configuration. The tuners are moved into their initialization position. A Load Pull or Source Pull is performed with the opposite tuner in the initialized position. This data is recorded into a file. The predicted transducer gain is calculated for each tuner position and is compared to the measured data by a computer program. The difference between the calculated and measured transducer gain is called delta GT and serves as our metric for the validity of the calibration. The mean of the delta GT values is used to determine the error correction factors for the system. The variance of the delta GTs is used as verification for the system and the error correction factors. With the corrections applied, the mean delta GT of each tuner must be less than a tenth of a dB for the verification to be valid. Typical values range from 0.05 to 0.09 dB. The variance of the delta GT is the metric for the verification of each tuner. The variance must be less than .15 dB. Typical values range from 0.08 to 0.12 dB. Appendix A shows the load pull file and the delta Gt calculation file.

3.5 Power Sweep

The theory behind S-parameters requires that the system be linear. Unfortunately, the universe is highly non-linear. There is a finite range over which the tuners will perform in a linear manner. The source of the nonlinearity is beyond the scope of this paper. The nonlinearities may be due to the noise or some structural factor. Nonlinear effects become more pronounced at higher gammas when the tuning probe is greatly perturbing the air waveguide.

The validity of a tuner point for measuring power sweeps can be determined by examining the range over which the power sweep at that point is linear. The tuner condition for this verification has one tuner in the configuration to be tested while the other is in the initial position. A power sweep is performed in this configuration. The criterion for success is that over the range to be measured, the peak to peak value is less than 0.2 dB and at high power the delta GT is less than 0.2 dB. These values are usually very easy to attain, and results are usually well within tolerances. This measurement can be used to determine the range over which a power sweep is valid in addition to determining the validity of the measurement itself. Appendix B contains a power sweep of a point on the Smith chart used to evaluate the calibration.

3.6 Conclusion

When performing measurements on a microwave device or system, it is not sufficient to merely collect data. An engineer needs a fundamental theory behind the measurements being performed and an understanding of how all of the measured values are derived. In this document, the derivations of fundamental calculations have been discussed. Where these derivations are integrated into the calibration of the tuner system has been outlined. The verification methods for our system have been defined.

Determining the veracity of the data of a system is almost as important as the data itself. If an engineer cannot articulate why the data is accurate or the degree to which it is believed to be accurate the engineer will be unable to defend the measurements if questioned. This document should serve as a basic primer for this knowledge as it applies to our high frequency test configuration.

References

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2. Edwards, M. L., *Microwave and RF Circuit*, Lecture notes, 1996.
3. Gonzoles, G., *Microwave Transistor Amplifiers*, Prentice-Hall, Inc., New Jersey, 1984.
4. Focus Microwaves, Application Note 48, Focus Microwaves, Inc., 2001.

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Appendix A. Sample Source Pull File

Sample Source Pull File SOURCE_PULL_JUN21.LPD

```
! Source Pull Measurement Data
!-----------------------------------------------------
! File = C:\FOCUS\DATA\NOHARM\VERIFY\SOURCE_PULL_JUN21.LPD
! Date = Wed Jun 21 13:48:44 2006
!-----------------------------------------------------
! Comment =
! Frequency = 40.0000 GHz
! Char.Impedances = Source: 50.00 Ohm, Load: 50.00 Ohm
! Load Impedance = 22.42 +j 17.34 Ohm
! Input Power = 29.80 dBm
! GAMMA_LD = Gl1fo=0.438<134.4(deg)
! IMPED_LD = Zl1fo=22.42+j17.34
! Setup: 20-40GHZ_NG_SETUP.SET, DUT REF.
! PreMatch:
! Impedance
!-----------------------------------------------------
Point      R       jX Pin[dBm] Gain[dB] GL_m[unit] GL_p[deg] GS_m[unit] GS_p[deg]
!-----------------------------------------------------
001    17.86     2.90    29.80    -2.02      0.438    134.38      0.475    172.40
002    17.65     4.64    29.75    -2.23      0.438    134.38      0.482    167.92
003    16.47     2.99    29.56    -2.20      0.438    134.38      0.506    172.34
004    17.41     6.63    29.59    -2.37      0.438    134.38      0.491    162.89
005    17.37     6.61    29.62    -2.40      0.438    134.38      0.492    162.95
006    15.85     1.11    29.41    -2.11      0.438    134.38      0.519    177.17
007    23.76     3.83    30.29    -1.75      0.438    134.38      0.359    168.74
008    18.13    -1.85    29.78    -1.68      0.438    134.38      0.468    184.88
009    14.04     2.40    28.92    -2.49      0.438    134.38      0.562    174.03
010    15.67     7.51    29.20    -2.73      0.438    134.38      0.532    161.13
011    17.10     8.44    29.43    -2.60      0.438    134.38      0.502    158.45
012    16.55    10.18    29.19    -2.88      0.438    134.38      0.519    154.39
013    16.39    10.08    29.23    -2.91      0.438    134.38      0.522    154.68
014    13.10     5.58    28.47    -2.94      0.438    134.38      0.589    166.35
015    13.53     0.37    28.82    -2.39      0.438    134.38      0.574    179.10
016    18.30    -3.83    29.76    -1.54      0.438    134.38      0.467    190.09
017    26.35     1.18    30.44    -1.49      0.438    134.38      0.310    176.26
018    22.40    13.34    29.87    -2.55      0.438    134.38      0.416    143.76
019    30.43     3.85    30.50    -1.64      0.438    134.38      0.248    166.15
020    23.06    -6.17    30.10    -1.20      0.438    134.38      0.377    197.73
021    15.28    -4.17    29.15    -1.84      0.438    134.38      0.535    190.49
022    12.37     0.53    28.27    -2.65      0.438    134.38      0.603    178.71
023    12.06     5.22    27.94    -3.14      0.438    134.38      0.615    167.37
024    13.78     9.73    28.46    -3.23      0.438    134.38      0.581    156.29
025    16.01    11.98    29.00    -3.12      0.438    134.38      0.537    150.31
026    15.44    13.68    28.61    -3.40      0.438    134.38      0.556    146.61
027    15.12    13.37    28.54    -3.40      0.438    134.38      0.562    147.43
028    12.02     8.97    27.66    -3.47      0.438    134.38      0.623    158.48
029    11.10     4.42    27.29    -3.26      0.438    134.38      0.639    169.37
030    11.56    -0.10    27.69    -2.64      0.438    134.38      0.625    180.25
031    13.86    -4.93    28.67    -1.84      0.438    134.38      0.569    192.18
032    20.59    -9.23    29.84    -1.11      0.438    134.38      0.433    204.86
033    32.89    -4.06    30.48    -1.17      0.438    134.38      0.212    196.13
034    31.27    12.75    30.30    -2.12      0.438    134.38      0.275    136.85
035    18.95    18.68    29.07    -3.45      0.438    134.38      0.507    133.82
036    31.65    18.74    30.06    -2.57      0.438    134.38      0.313    121.47
037    41.61     1.09    30.46    -1.47      0.438    134.38      0.092    171.95
038    27.22   -13.51    30.10    -0.94      0.438    134.38      0.338    220.60
039    16.40   -10.20    29.07    -1.39      0.438    134.38      0.523    205.62
040    12.10    -4.77    27.86    -2.27      0.438    134.38      0.613    191.57
041    10.59    -0.12    26.92    -3.04      0.438    134.38      0.650    180.28
042    10.24     4.11    26.50    -3.46      0.438    134.38      0.662    170.19
043    10.83     8.24    26.74    -3.76      0.438    134.38      0.652    160.41
044    12.54    12.53    27.48    -3.83      0.438    134.38      0.619    150.18
```

045	14.42	15.12	28.09	-3.74	0.438	134.38	0.584	143.77
046	13.54	16.68	27.33	-4.09	0.438	134.38	0.610	140.72
047	12.73	15.39	27.02	-4.09	0.438	134.38	0.624	143.78
048	10.75	10.96	26.08	-4.18	0.438	134.38	0.660	154.17
049	9.72	6.85	25.43	-3.97	0.438	134.38	0.680	163.80
050	9.49	3.03	25.42	-3.42	0.438	134.38	0.682	172.82
051	9.85	-0.99	25.99	-2.96	0.438	134.38	0.671	182.36
052	11.10	-5.51	26.94	-2.33	0.438	134.38	0.641	193.20
053	14.30	-11.27	28.23	-1.41	0.438	134.38	0.573	207.46
054	22.90	-17.54	29.42	-0.84	0.438	134.38	0.431	226.44
055	43.25	-14.35	30.17	-1.14	0.438	134.38	0.168	253.54
056	47.58	15.32	30.08	-2.14	0.438	134.38	0.157	90.07
057	26.75	24.77	29.33	-3.28	0.438	134.38	0.421	115.31
058	14.66	22.05	26.96	-4.48	0.438	134.38	0.610	129.22
059	22.76	29.35	28.38	-4.21	0.438	134.38	0.510	110.90
060	46.57	32.22	29.40	-3.20	0.438	134.38	0.318	77.63
061	68.03	-7.03	29.66	-1.95	0.438	134.38	0.164	342.10
062	33.45	-28.01	29.20	-1.00	0.438	134.38	0.370	257.98
063	17.32	-19.59	28.06	-1.08	0.438	134.38	0.543	227.17
064	11.89	-11.75	26.66	-1.84	0.438	134.38	0.633	207.87
065	9.80	-5.95	25.27	-2.63	0.438	134.38	0.676	194.10
066	8.96	-1.51	24.26	-3.19	0.438	134.38	0.696	183.57
067	8.70	2.34	23.70	-3.67	0.438	134.38	0.704	174.49
068	8.84	5.88	23.60	-4.01	0.438	134.38	0.703	166.16
069	9.34	9.65	24.08	-4.25	0.438	134.38	0.695	157.42
070	10.37	13.70	24.95	-4.35	0.438	134.38	0.677	148.16
071	11.93	17.58	25.87	-4.47	0.438	134.38	0.651	139.38

Sample Gt Calc File SOURCE_PULL_JUN20.txt

Number	R	jX	Gt(Calc)	GT(calc dB)	Gain(meas)	Delta
1	20.79	8.78	0.65	-1.84	-1.82	-0.02
2	20.62	11.91	0.61	-2.14	-2.09	-0.05
3	19.40	9.31	0.63	-2.02	-2.03	0.01
4	19.80	13.84	0.58	-2.40	-2.38	-0.02
5	19.77	13.83	0.58	-2.40	-2.39	-0.01
6	17.92	7.42	0.63	-2.00	-2.00	-0.00
7	28.18	9.86	0.71	-1.49	-1.38	-0.11
8	20.57	3.63	0.72	-1.42	-1.43	0.01
9	16.31	9.02	0.58	-2.36	-2.39	0.03
10	18.20	15.36	0.53	-2.73	-2.73	-0.00
11	20.39	16.74	0.55	-2.61	-2.61	0.00
12	19.81	18.39	0.52	-2.83	-2.84	0.01
13	19.55	18.34	0.52	-2.85	-2.86	0.01
14	15.99	13.04	0.52	-2.82	-2.82	-0.00
15	15.93	6.71	0.61	-2.18	-2.18	-0.00
16	20.47	1.47	0.75	-1.25	-1.16	-0.09
17	30.63	6.51	0.76	-1.18	-1.09	-0.09
18	28.63	22.70	0.57	-2.45	-2.39	-0.06
19	35.48	8.38	0.76	-1.21	-1.17	-0.04
20	25.77	-1.51	0.83	-0.79	-0.78	-0.01
21	17.19	1.46	0.70	-1.53	-1.59	0.06
22	14.26	6.84	0.57	-2.45	-2.51	0.06
23	14.06	12.32	0.49	-3.07	-3.11	0.04
24	16.86	18.09	0.48	-3.20	-3.19	-0.01
25	19.16	20.67	0.49	-3.13	-3.14	0.01
26	18.38	23.34	0.45	-3.50	-3.49	-0.01
27	18.18	22.80	0.45	-3.48	-3.43	-0.05
28	14.05	17.61	0.43	-3.66	-3.58	-0.08
29	12.82	11.80	0.47	-3.27	-3.28	0.01
30	13.38	6.25	0.56	-2.54	-2.51	-0.03
31	15.62	0.92	0.68	-1.66	-1.61	-0.05
32	22.91	-4.13	0.85	-0.72	-0.61	-0.11

33	36.83	-1.38	0.85	-0.69	-0.58	-0.11
34	41.02	19.01	0.67	-1.77	-1.72	-0.05
35	24.75	30.08	0.46	-3.36	-3.39	0.03
36	43.00	27.63	0.59	-2.26	-2.24	-0.02
37	48.06	3.50	0.79	-1.00	-0.85	-0.15
38	28.48	-9.01	0.92	-0.35	-0.32	-0.03
39	18.12	-4.63	0.80	-0.94	-1.07	0.13
40	13.85	1.21	0.64	-1.93	-2.12	0.19
41	12.20	6.63	0.52	-2.82	-2.97	0.15
42	12.30	11.60	0.46	-3.36	-3.47	0.11
43	12.84	16.67	0.41	-3.82	-3.83	0.01
44	14.92	22.24	0.40	-3.97	-3.95	-0.02
45	17.66	25.09	0.42	-3.78	-3.74	-0.04
46	14.53	27.14	0.35	-4.57	-4.62	0.05
47	14.75	25.12	0.37	-4.31	-4.24	-0.07
48	13.12	19.58	0.39	-4.08	-3.92	-0.16
49	11.55	14.29	0.41	-3.86	-3.77	-0.09
50	11.04	10.23	0.44	-3.52	-3.49	-0.03
51	11.56	5.73	0.52	-2.87	-2.80	-0.07
52	13.05	0.66	0.63	-2.01	-1.94	-0.07
53	16.10	-5.28	0.78	-1.07	-0.96	-0.11
54	23.92	-11.89	0.94	-0.28	-0.22	-0.06
55	44.04	-14.34	0.91	-0.40	-0.32	-0.08
56	60.75	15.73	0.69	-1.63	-1.58	-0.05
57	36.25	37.28	0.49	-3.12	-3.10	-0.02
58	18.18	35.06	0.34	-4.67	-4.78	0.11
59	31.32	46.66	0.39	-4.11	-4.18	0.07
60	71.63	40.41	0.54	-2.69	-2.76	0.07
61	69.65	-21.16	0.79	-1.04	-1.05	0.01
62	31.05	-24.68	0.99	-0.04	0.04	-0.08
63	18.08	-13.97	0.92	-0.38	-0.47	0.09
64	13.36	-6.00	0.74	-1.33	-1.53	0.20
65	11.22	0.29	0.58	-2.34	-2.52	0.18
66	10.72	5.03	0.50	-3.00	-3.15	0.15
67	10.34	9.08	0.44	-3.58	-3.64	0.06
68	10.00	13.61	0.38	-4.24	-4.32	0.08
69	10.83	18.58	0.35	-4.57	-4.55	-0.02
70	11.69	23.43	0.33	-4.88	-4.78	-0.10
71	14.75	29.67	0.33	-4.79	-4.67	-0.12

Mean 21.95 10.99 0.59 -2.49 -2.48 -0.01 std
0.08

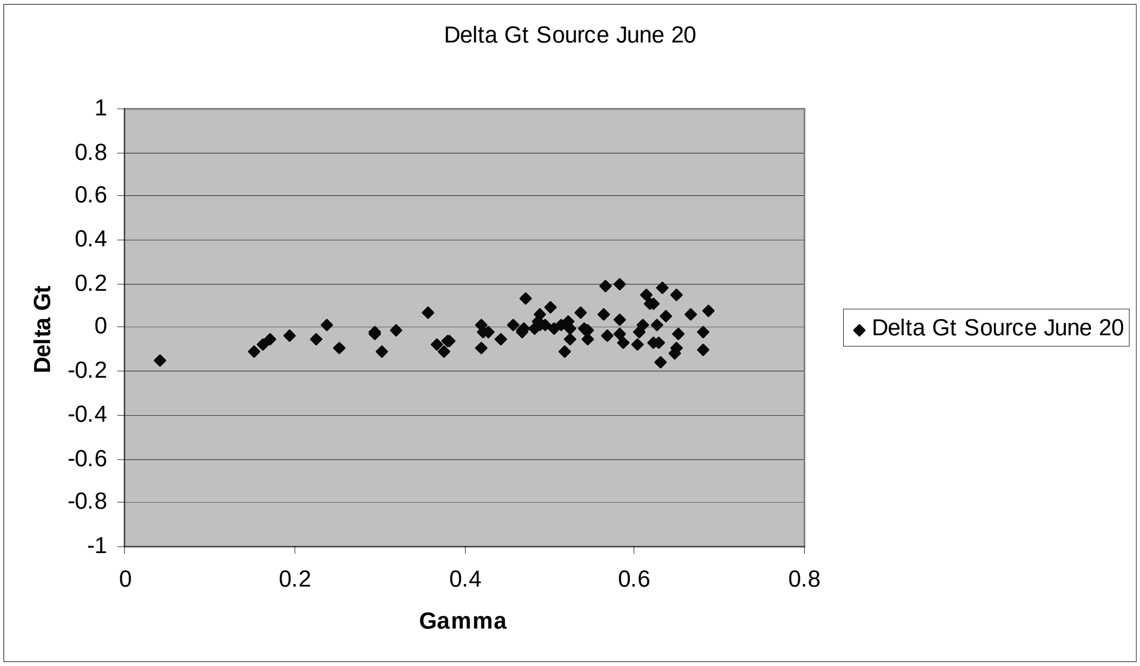

Figure A-1. Reflection coefficient versus Delta Gt.

Sample power sweep on thru. Calculated Gt is -3.0.

```
!TITLE:
!HEADER: GIN_INIT_GOUT_HIGH.SAT,Mon Jun 05 14:15:07 2006
!FREQUENCY: 40.020 GHz
!Char.Impedances = Source: 50.00 Ohm, Load: 50.00 Ohm
!COMMENT: Freq=40.020(GHz), Gs=0.364 <Gs=172.6(deg), Gl=0.691 <Gl=115.8(deg)
!GAMMA_SR: Gs1fo=0.364<172.6(deg)
!IMPED_SR: Zs1fo=23.38+j2.54
!GAMMA_LD: Gl1fo=0.691<115.8(deg)
!IMPED_LD: Zl1fo=12.58+j29.91
!Setup: AA_SETUP.SET, DUT REF.
!PreMatch:
!XLABEL: Pin[dBm]
!NAMES: Pin[dBm] Pout[dBm] Gain[dB]  Igs[mA]   Vgs[V]  Ids[mA]   Vds[V] Colec.Eff[%] P.A.Eff[%] P.Source1[dBm]
!UNITS:
   20.31     17.54    -2.17    -0.5760800    -0.0001200    0.000     0.0000000         0.00       0.00         -23.00
   22.19     19.10    -2.49    -0.5989800    -0.0000800    0.000     0.0000000         0.00       0.00         -21.00
   24.00     20.68    -2.72    -0.6200000    -0.0003200    0.000     0.0000000         0.00       0.00         -19.00
   25.76     22.31    -2.85    -0.5789400    -0.0001600    0.000     0.0000000         0.00       0.00         -17.00
   27.38     23.81    -2.97    -0.5711800     0.0001600    0.000     0.0000000         0.00       0.00         -15.00
   28.82     25.11    -3.11    -0.5844400    -0.0001600    0.000     0.0000000         0.00       0.00         -13.00
   29.99     26.18    -3.21    -0.5643600    -0.0001200    0.000     0.0000000         0.00       0.00         -11.00
   30.89     27.24    -3.05    -0.4736000    -0.0002800    0.000     0.0000000         0.00       0.00          -9.00
   31.53     27.83    -3.10    -0.6120600    -0.0003600    0.000     0.0000000         0.00       0.00          -7.00
   31.84     28.05    -3.19    -0.5863800    -0.0003600    0.000     0.0000000         0.00       0.00          -5.00
```

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